A high-performance Silicon Tracker for the CBM experiment at FAIR

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for the CBM Collaboration

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<u>Overview:</u>

- The future accelerator facility FAIR in Darmstadt
- The **C**ompressed **B**aryonic **M**atter experiment
- The CBM Silicon Tracker
  - Performance requirements
  - Detector concept
  - R&D directions

Facility for Antiproton and Ion Research

FAIR: Future international accelerator complex at GSI, Darmstadt, Germany

→ see talk of L. Schmitt

Project Management:

Start of construction: 2007/2008

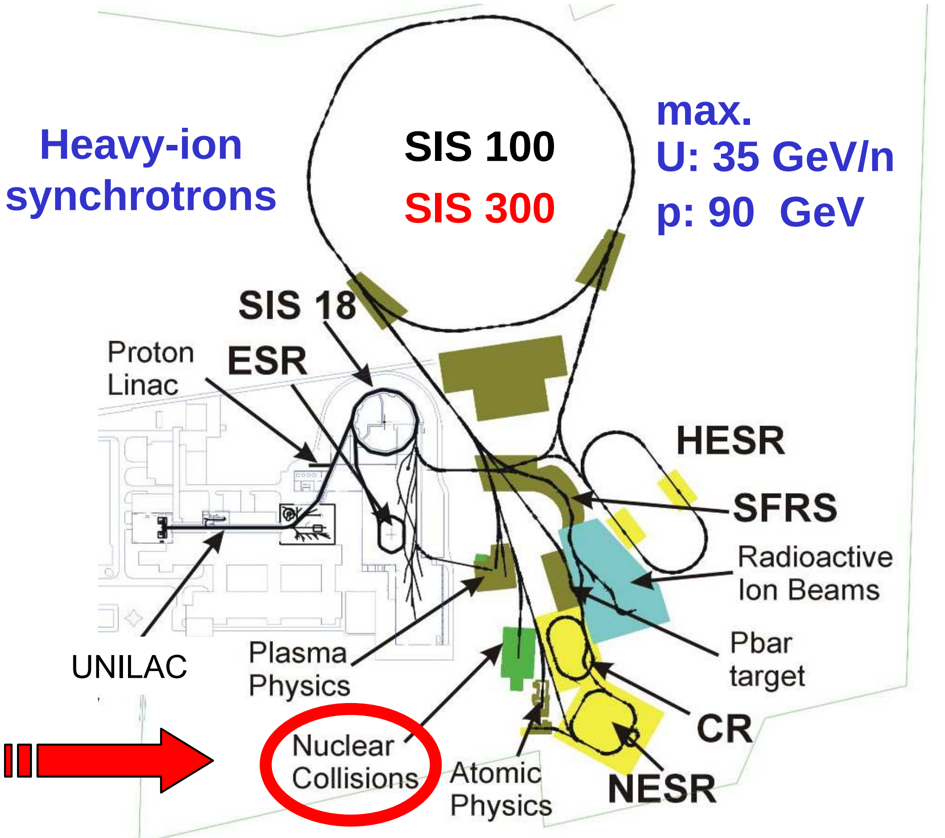
First beams: 2011

Full operation, **CBM**: 2015

Research program includes physics with:

- Radioactive ion beams:
  Structure of nuclei far from stability
- Anti-proton beams:
  Hadron spectroscopy, anti hydrogen
- Ion and laser induced plasmas:
  High energy density in matter
- High-energy nuclear collisions:
  Strongly interacting matter at
  high baryon densities

Compressed **B**aryonic **M**atter
Experiment



CBM - Physics Motivation

Strong-interaction physics:

confinement, broken chiral symmetry, hadron masses.

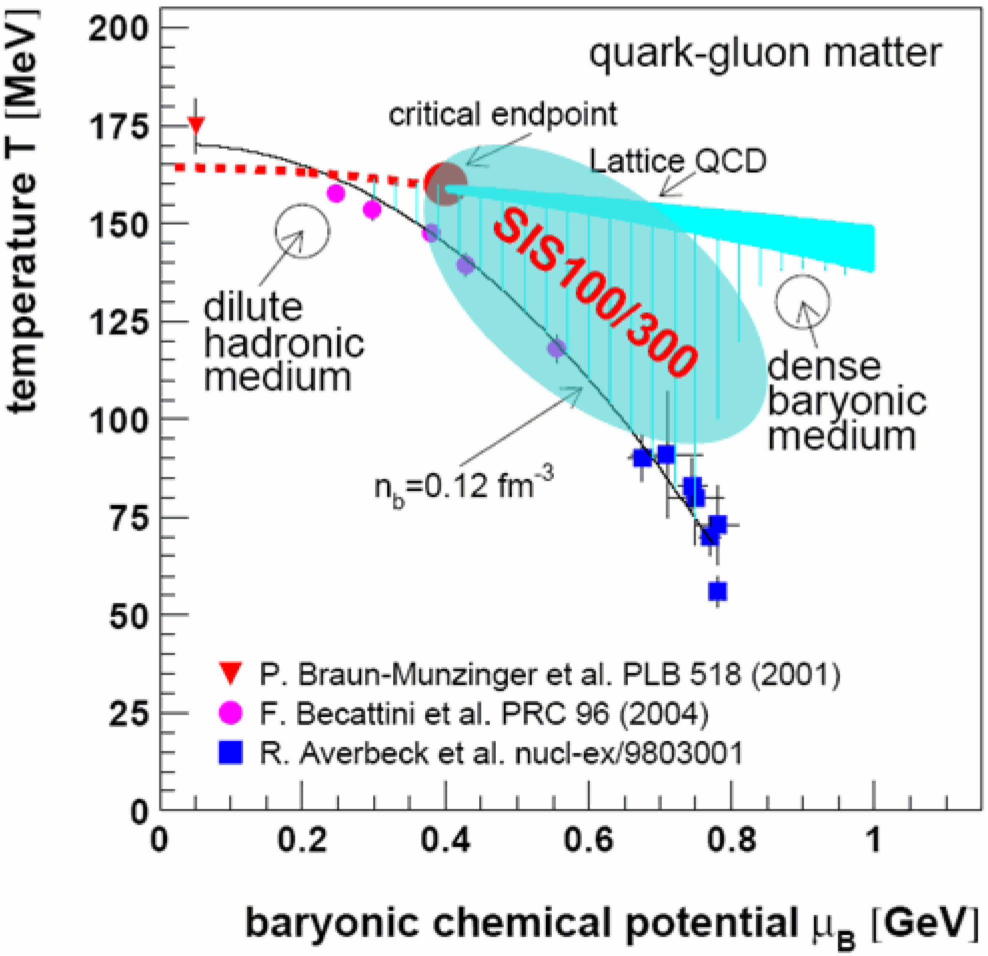
CERN-SPS and RHIC:

- indications for a new state of matter: „Quark Gluon Plasma“.
- Produced at high T and low μ_B.
- LHC: even higher T, lower μ_B.

QCD phase diagram:

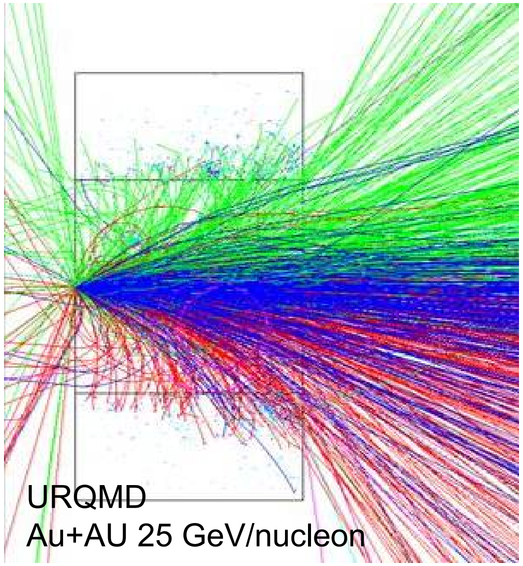
→ poorly known at low T, high μ_B:
→ new measurements at **FAIR**: with highest baryon densities, and with new probes!

⇒ CBM Experiment



Physics and Observables

Physics	**Observables**
In-medium modifications of hadrons: Onset of chiral symmetry restoration	$\rho, \omega, \phi \rightarrow e^+e^-$ $(\mu^+ \mu^-)$ open charm: D^0, $D^{\pm}$
Indications for deconfinement: Anomalous charmonium suppression ?	$D^0, D^{\pm}, J/\psi \rightarrow e^+e^-$ $(\mu^+ \mu^-)$
Strangeness in matter: Enhanced strangeness production	$K, \Lambda, \Sigma, \Xi, \Omega$
Critical point: Event-by-event fluctuations	π, K



Open charm measurement:
One of the prime interests of CBM, one of the most difficult tasks!

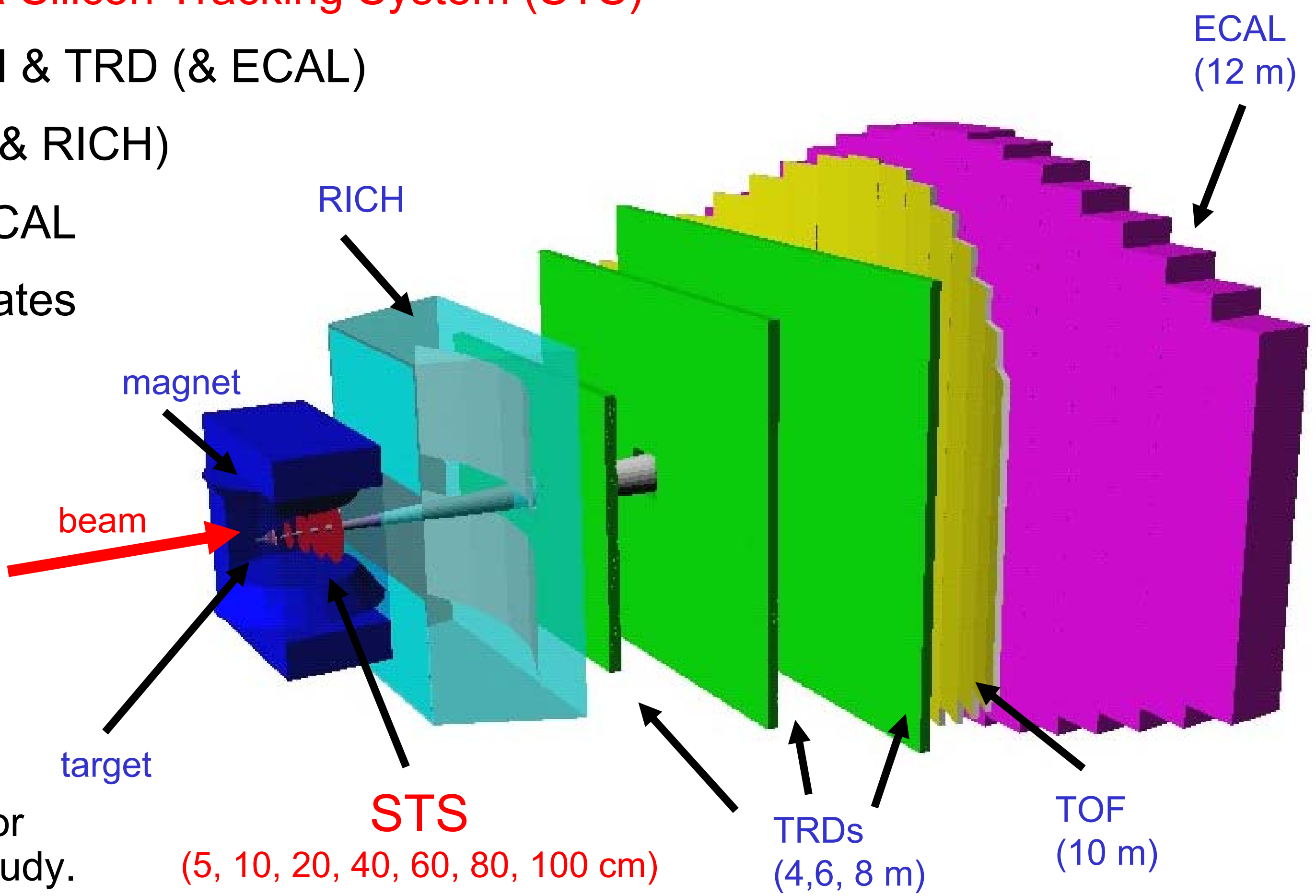
Tracking challenge:

- up to 10^7 Au+Au reactions/sec @ 25 GeV/nucleon
- ~ 1000 charged particles/event, up to ~100 tracks/cm^2/event
- momentum measurement with resolution < 1%
- secondary vertex reconstruction (≈ 30 μm)
- high speed data acquisition and trigger system

The CBM Experiment

- Conceptional Design -

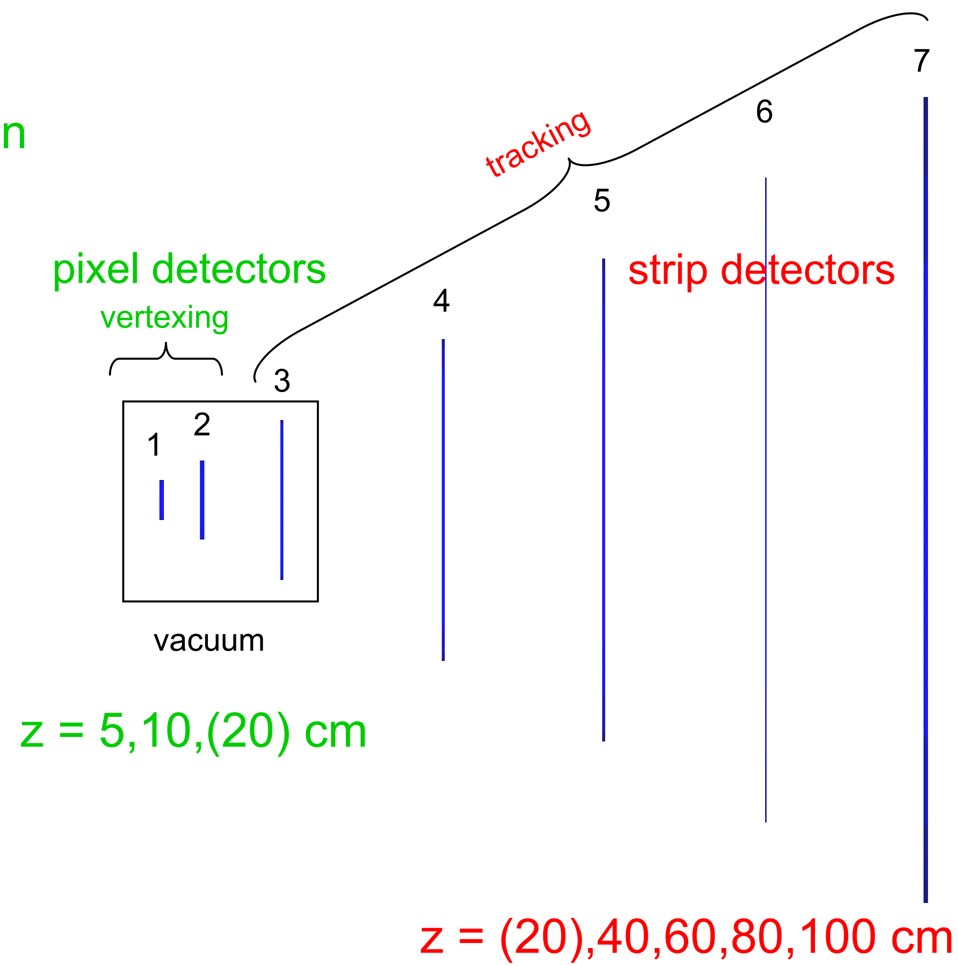
- Tracking, momentum measurement, vertex reconstruction:
  Exclusively with a Silicon Tracking System (STS)
- Electron ID: RICH & TRD (& ECAL)
- Hadron ID: TOF (& RICH)
- Photons, π^0, μ: ECAL
- High interaction rates
- No central trigger
- Data-push r/o
  architecture



Further specific detector configurations under study.

The Silicon Tracking System
- Conceptional Geometry -

- Assume 7 planes
  - 2 or 3 thin pixel stations:
    → secondary vertex detection
    (benchmark: open charm)
  - 4 or 5 thin strip stations:
    → tracking
- Acceptance: 50 to 500 mrad
- First plane:
  z=5cm ; size 25 cm^2
- Last plane:
  z=100cm; size ~1 m^2
- Magnetic dipole field:
  ~ 1Tm, $\delta p/p$ <1% @ p=1 GeV



Challenge: Open Charm Reconstruction

Some hadronic decay modes:

$D^{\pm}$ ($c\tau$ = 317 μm):
$D^+ \rightarrow K^-\pi^+\pi^+$ (9 $\pm$ 0.6%)

D^0 ($c\tau$ = 124.4 μm):
$D^0 \rightarrow K^-\pi^+$ (3.9 $\pm$ 0.09%)

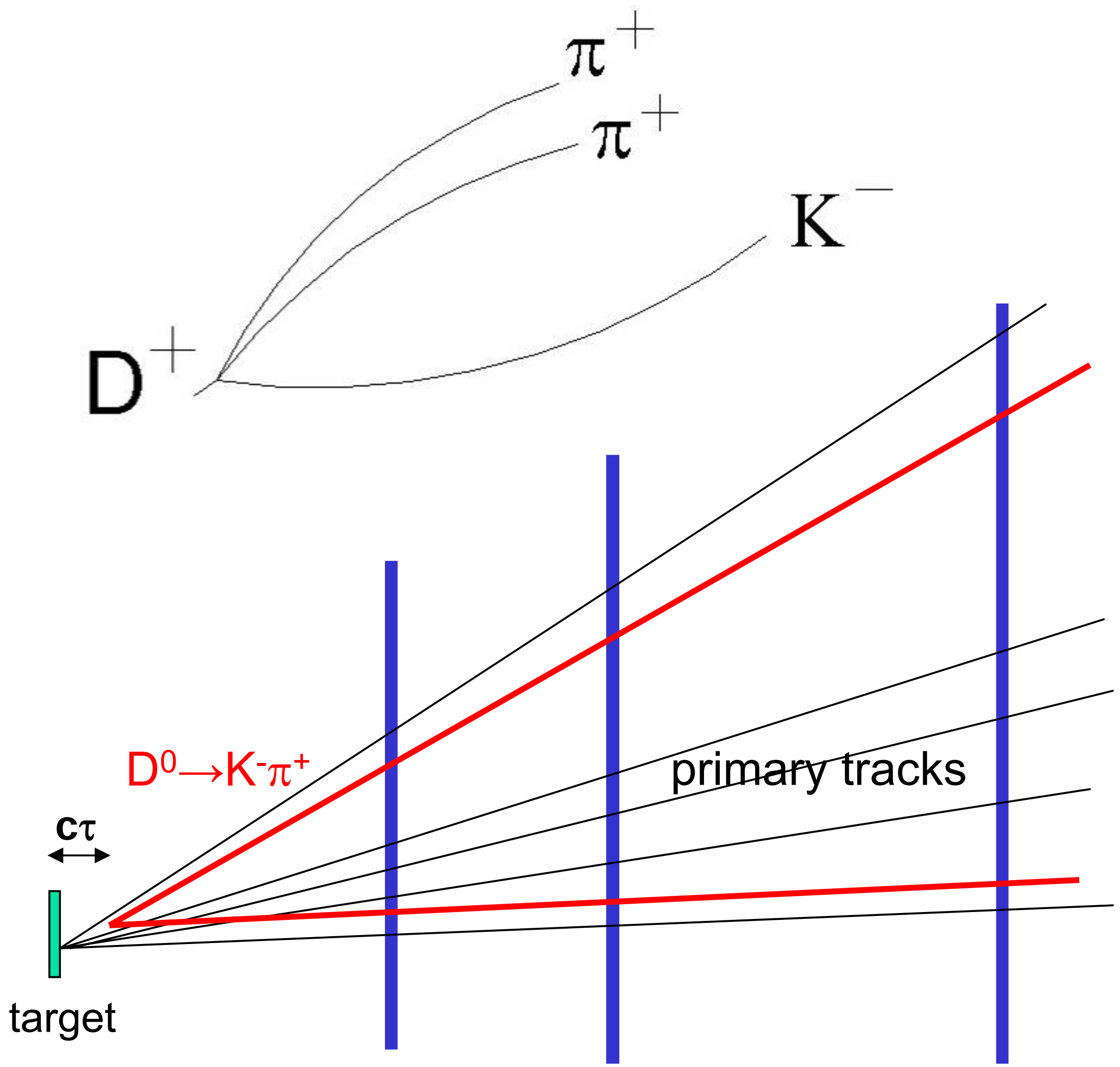
$\Rightarrow$ High-granularity sensors.
$\Rightarrow$ Thin tracking stations.

$$\Delta x \approx d_{1\rightarrow 2} \frac{14\ \text{MeV}}{p} \sqrt{\frac{x}{X_0}}$$

$$\Delta x = 10\ \mu\text{m};\ d_{1\rightarrow 2} = 50\ \text{mm}$$

$$\frac{x}{X_0} = 0.18\,\% \ \left(p = 3\ \text{GeV}\right)$$

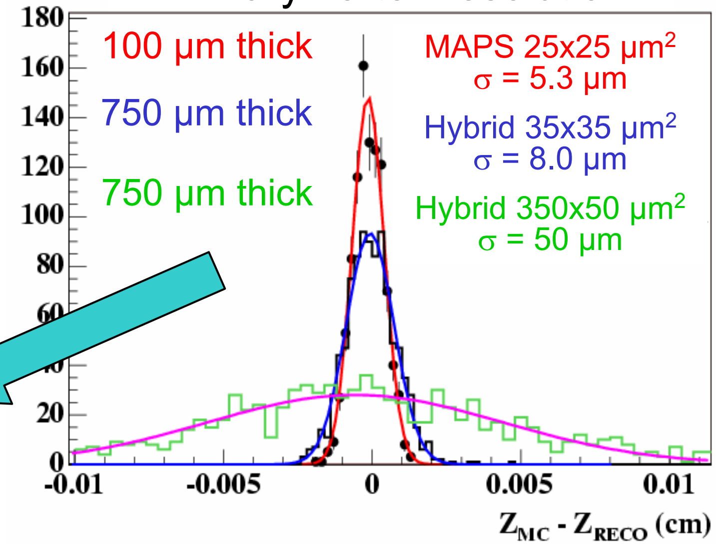
Rare probe:
$\Rightarrow$ High level charm trigger.



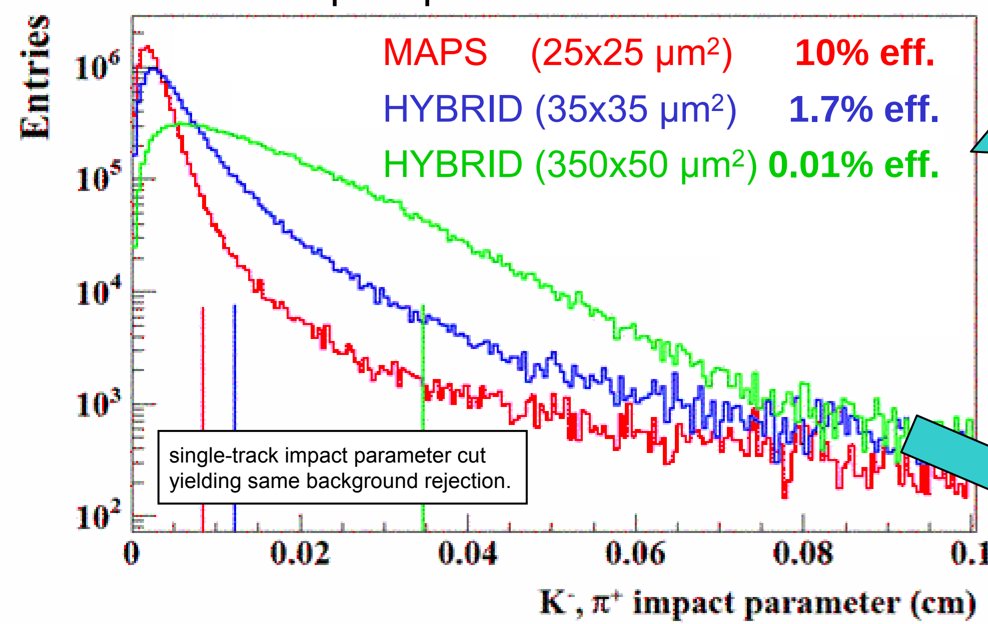
Pixel Detectors for Vertexing

What kind of **pixel detectors** can do the job?
Study of different detector types, characterized by their material budgets and pixel sizes:

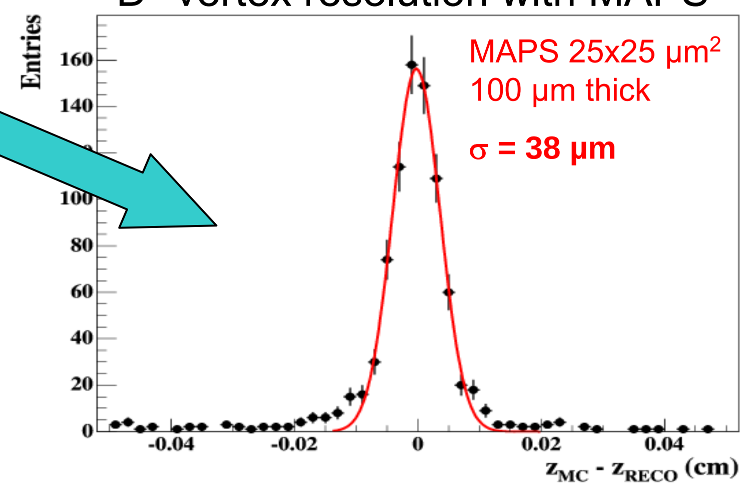
Primary vertex resolution



D⁰ impact parameter measurement

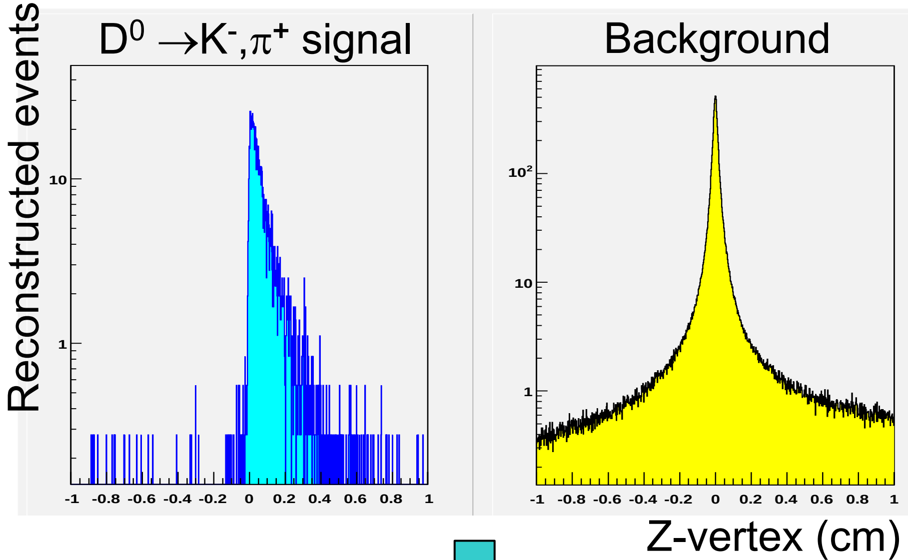


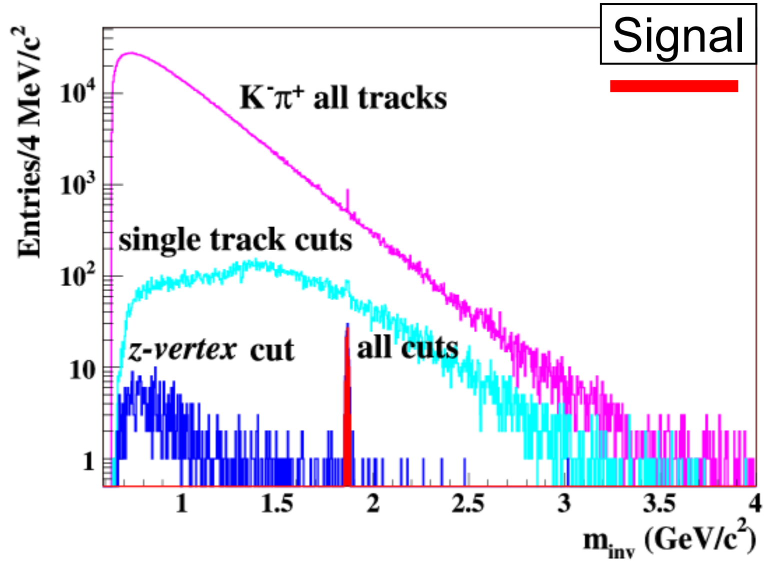
D⁰ vertex resolution with MAPS



⇒ small pixels ≤ 25 x 25 µm²
⇒ (thin sensors ~ 100 µm)

$D^0 \rightarrow K^-\pi^+$ reconstruction using MAPS



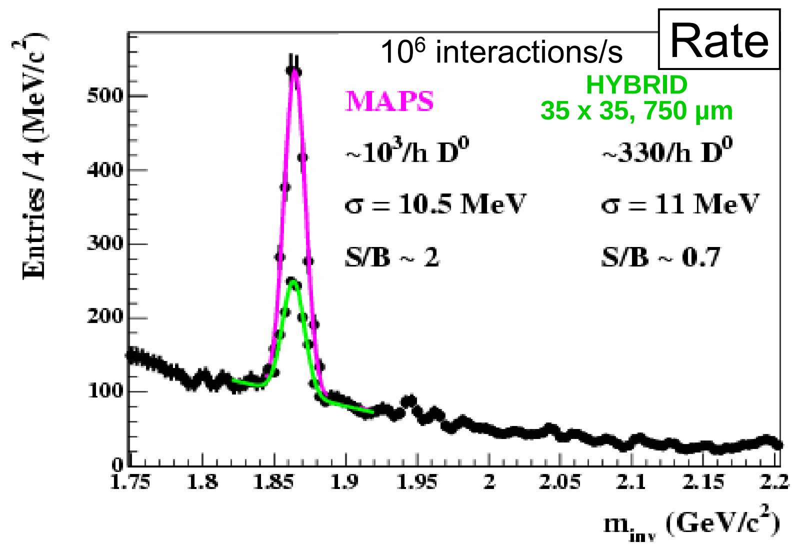


Cuts

cut	optimized value	signal efficiency %
χ^2 *distance to the primary vertex*	$3.5\,\sigma$	53
p-cut	$1.0\ GeV/c$	72
p_t*-cut*	$0.5\ GeV/c$	61
z-vertex cut	$250\ \mu m$	54
D^0 *pointing cut*	$30\ \mu m$	99
geometric vertex χ^2 *cut*	≤ 5	91
all cuts	-	10.4

study by I. Vassiliev, GSI

~10 % efficiency



Pixel Detector Requirements

- Small pixels – less than 25 x 25 μm^2
- Thin – less than ~100 μm silicon
- Radiation hard > 10^{14} n_{equiv}/cm^2
- Fast readout – interaction rate up to 10^7/s

Such a detector does not exist !
Two possible R&D directions:

Monolithic Active Pixel Sensors (MAPS):

- small pixels: 25 x 25 μm^2
- thin: standard 120 μm; study: 50 μm
- spatial resolution: ~3 μm
- too slow for CBM: ~ms/Mpixel full frame
- limited rad. hardness (bulk damage)

⇒ Improve r/o time, radiation tolerance.

Hybrid Pixel Detectors (LHC type):

- fast readout
- radiation hard
- too large pixels: 50 x ~400 μm^2
- spatial resolution: ~15 (115) μm
- thick: standard > 350 μm

⇒ Reduce pixel size and thickness.

We started persuing the MAPS option, together with IReS Strasbourg.
Alternative to consider: DEPFET sensors (MPI Munich).

R&D goals with MAPS: Radiation tolerance & readout speed

R&D goals with MAPS:

radiation tolerance: ~$10^{12} \rightarrow 10^{13}$ 1 MeV $n_{equiv.}$

readout time: 10 μsec, column parallel r/o, in reach in next years

Expected situation in CBM:

Fluence at 1st MAPS station:

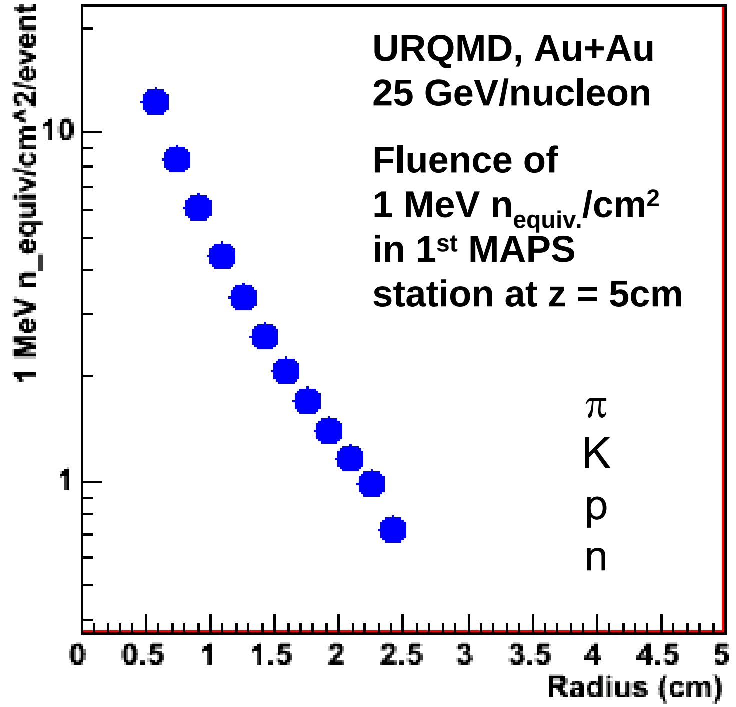
~10 1-MeV $n_{equiv.}$ per event

$\rightarrow$ detector partly destroyed after 10^{12} reactions
$\rightarrow$ corresponds to ~10^5 D mesons detected (decent measurement!)

Possible running conditions:

a) ~1 day detector lifetime at 10^7 reactions/s, 100 events piled up, or

b) ~ 4 month detector lifetime at 10^5 reactions/s, no pile-up events.



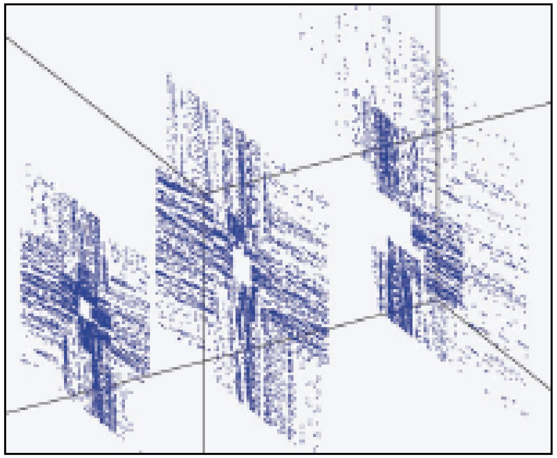
Consider also future developments:
Hybrid pixels ~ 50x50 µm^2, few hundred µm thick, with higher radiation tolerance and faster readout.

Tracking in Silicon Strip Stations

First attempts:
Problem - High occupancy with many combinatorial hit points in silicon strip stations.

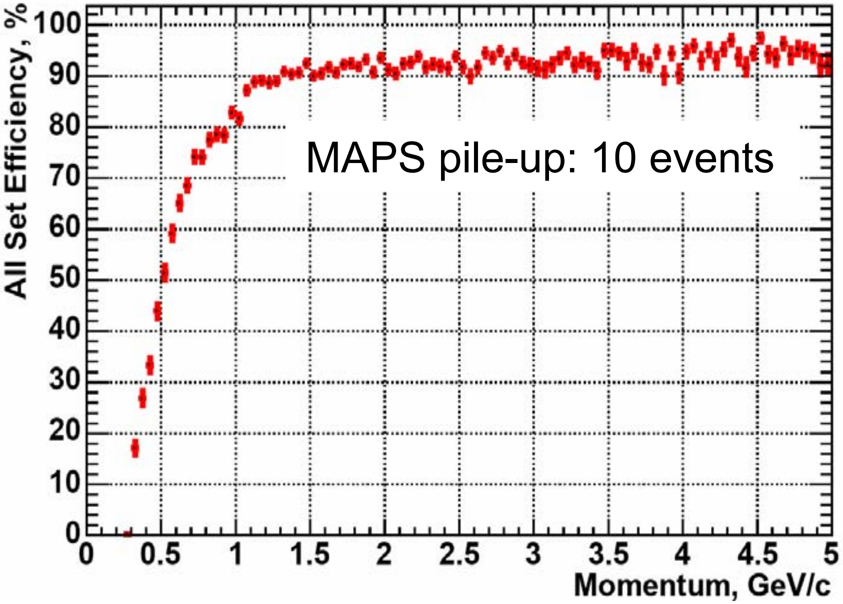
Recent approach:
Cellular automaton technique: Works!

Example:
4 strip stations + 3 MAPS stations



MAPS pile-up (events)	0	5	10	20	50	100
Track category	Efficiency (%)					
Reference primary	96.37	96.08	95.84	95.15	93.79	91.47
Ref. set	92.87	92.55	92.30	91.58	90.06	87.94
All set	86.17	85.52	84.97	83.69	80.97	78.47
Extra set	63.33	61.57	59.98	56.79	51.60	47.88
Clone	0.00	0.00	0.00	0.00	0.00	0.00
Ghost	2.47	3.59	4.55	6.53	9.85	13.33

I. Kisel, Heidelberg, and S. Gorbunov, DESY



Tracking Requirements

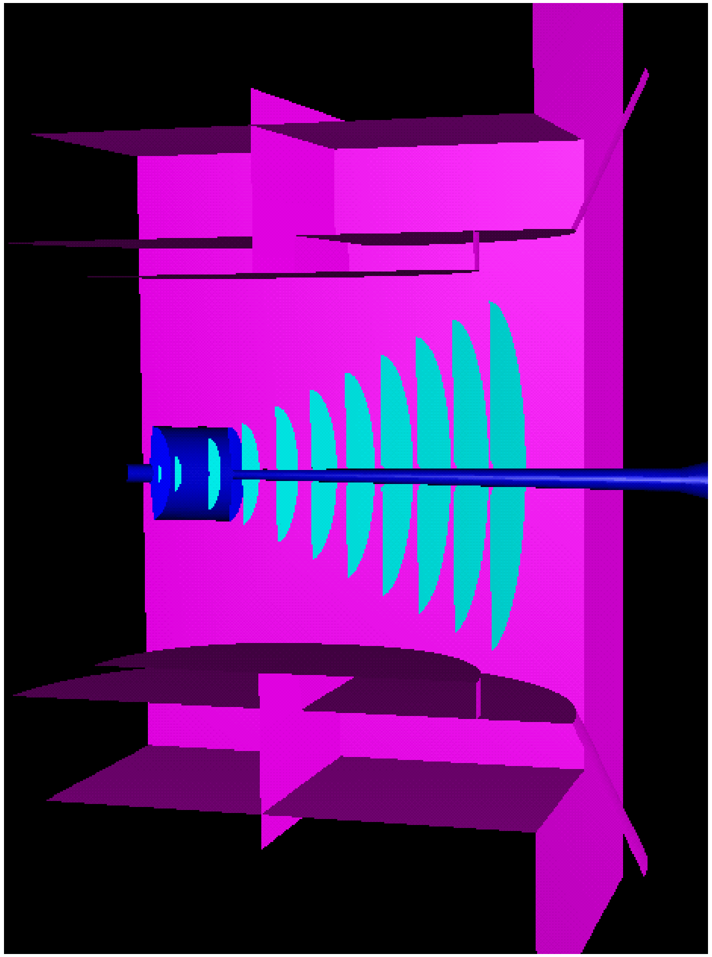
- Tracking with microstrip and pixel stations:
  Works despite of combinatorial hits and pile-up!

  But: Noise, misalignment,
  detector inefficiencies
  etc. not taken into account!

- Consider more tracking redundancy!

  Comprehensive study on the way to optimize the Silicon Tracker's layout, including:

  - more tracking stations,
  - several strip geometries,
  - additional (hybrid?) pixel detectors supporting the tracking, and
  - detailed modeling of the detectors.



Pixel Detector – Module Concept

CMOS MAPS chips for CBM:

- size: ~0.5 x 1 cm^2
- ~50% sensor, ~50% r/o.
- column readout in ~10 µs

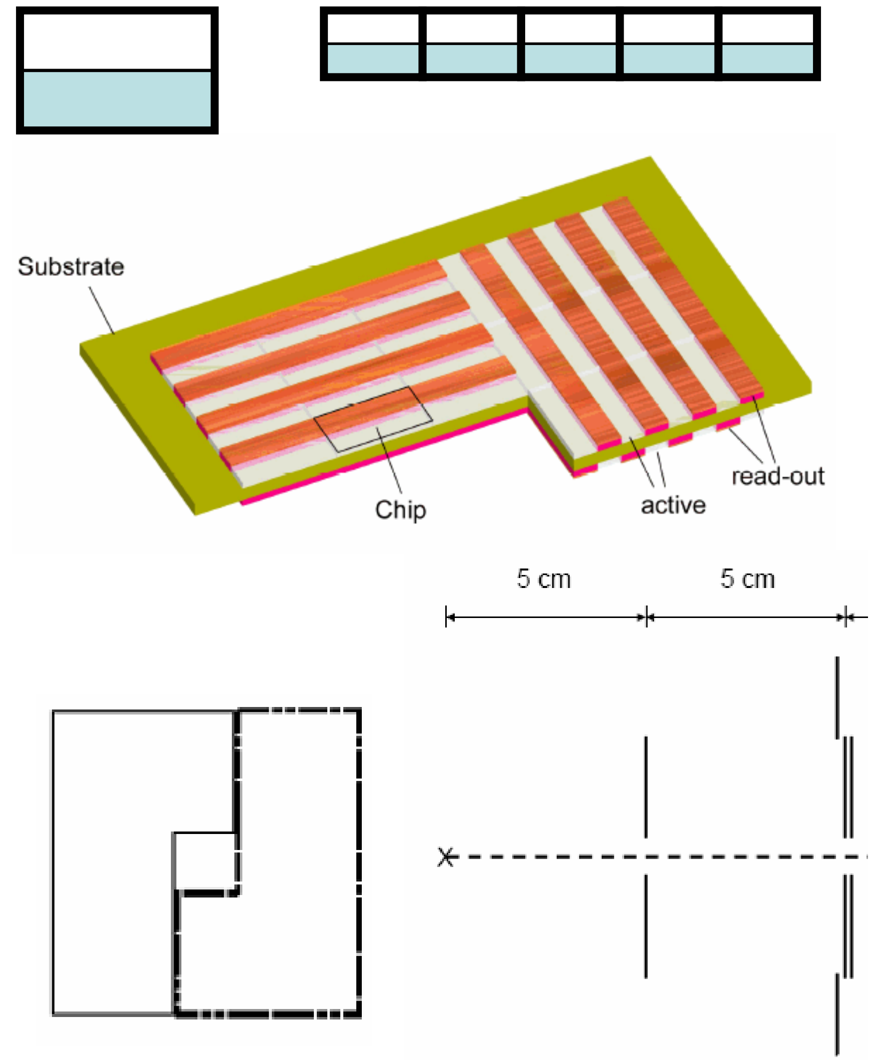
CBM MAPS ladders with 4 or 5 "chips".

Detector module: BTeV inspired design

ladders mounted on either side of a substrate providing (active?) cooling.

Active cooling support:

- a carbon fiber structure with micro pipes? ~ 0.3% X_0
- glass or silicon wafers with buried micro channels? ~ 0.1-0.3% X_0

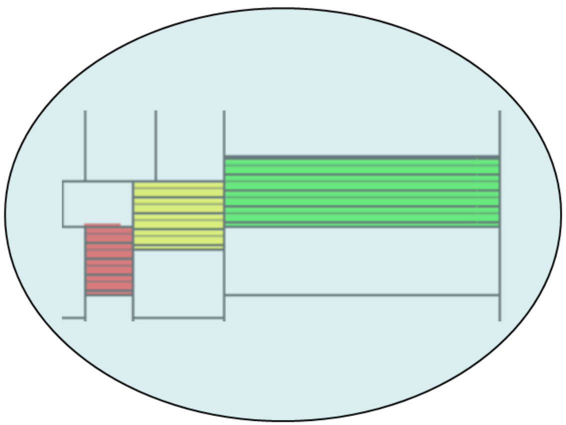


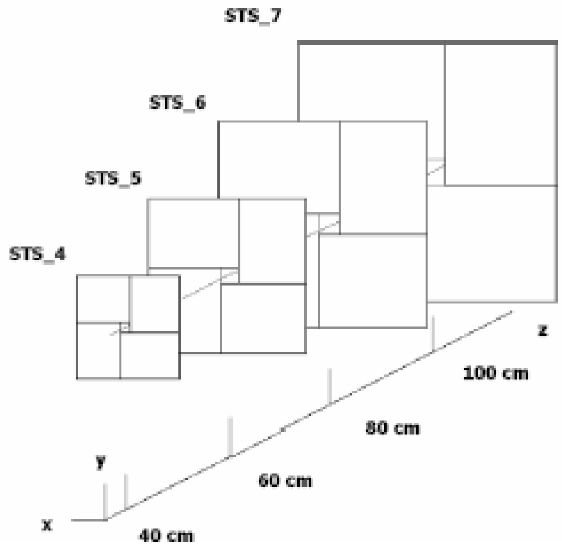
Strip Detector – Modules & Stations

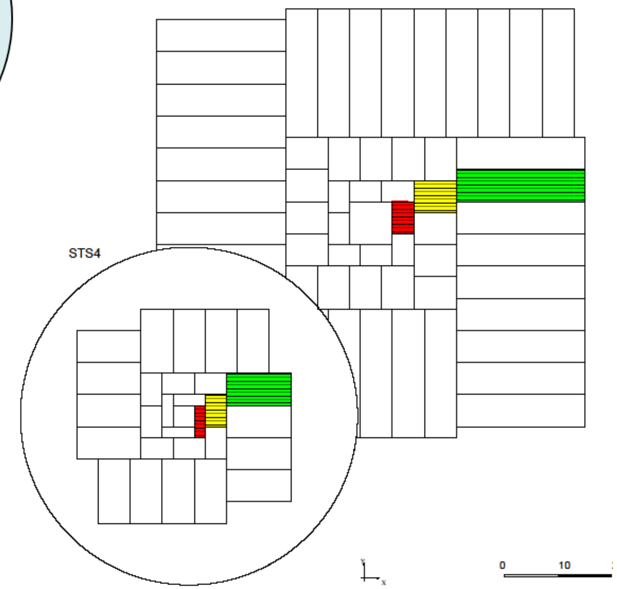
<u>Four detector stations:</u>
built from a few wafer types.

<u>Basic sensor elements:</u>
200 μm thick silicon wafers.
double-sided, rad-tolerant.
50 μm (25 μm?) strip pitch.

Inner : 6x4 cm
Middle : 6x12 cm
Outer : 6X20 cm







<u>Study of:</u>

- strip length, pitch, stereo angle
  (to reduce fake hits)
- single-sided sensor option
- location of read-out chips
  (on sensor / outside acceptance)

Summary

CBM – High-rate fixed-target heavy-ion experiment planned at FAIR/SIS300.
– Strong-interaction physics, high baryon densities: Au+Au up to 35 GeV/nucl.
– Challenge: Rare probes - Open charm, low-mass vector mesons → di-leptons.

Experimental concept, new to heavy-ion physics:
- Tracking exclusively with a high-performance Silicon Tracker.
- **Very important detector system, key to the physics of CBM.**

Silicon Tracker performance requirements:
- Efficient tracking, high momentum resolution.
- High-resolution vertexing. Benchmark: Open charm.
  → Small pixels, thin, radiation tolerant, fast r/o. **Beyond state-of-the-art!**

Detector R&D started:
- Thin, fine-pitch double-sided microstrip sensors (tracking).
- **MAPS with improved radiation hardness, readout speed (vertexing).**
- Readout electronics.

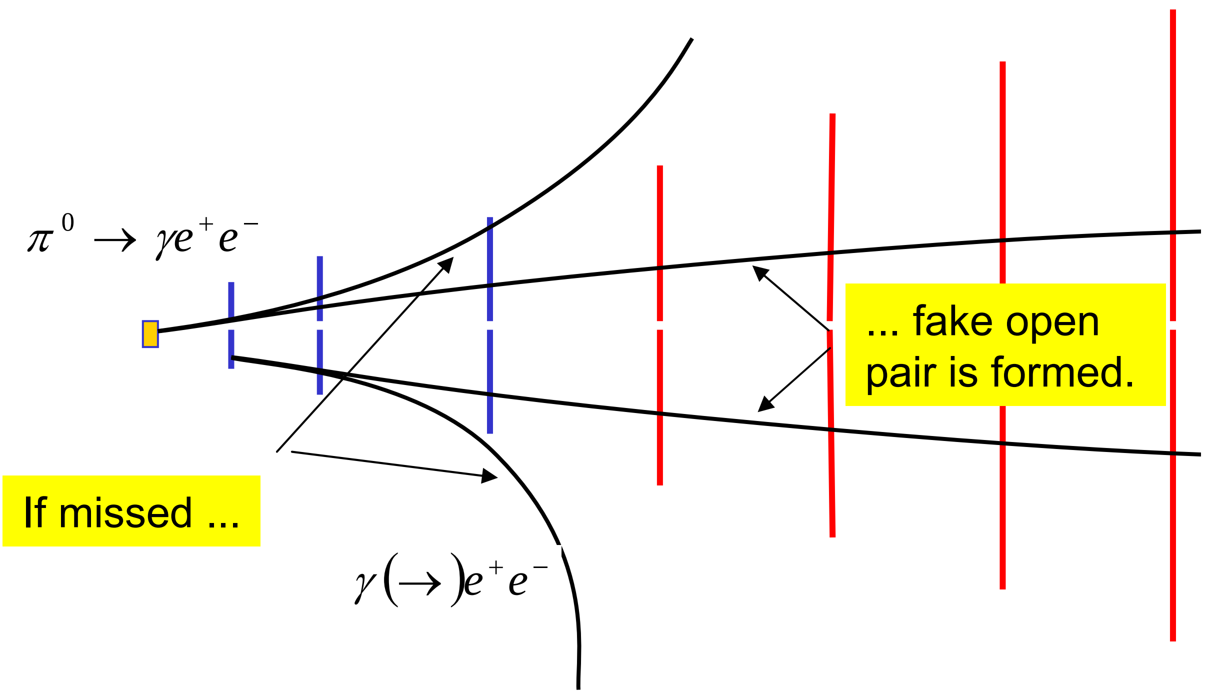
Open for new ideas! http://www.gsi.de/fair/experiments/CBM/index_e.html

Discussion

Low Mass Dilepton Spectroscopy

Signal: vector meson decays
$\rho, \omega, \phi \rightarrow e^+e^-$

Background:
π^0 decay (365/event)
$\pi^0 \rightarrow e^+e^-\gamma$ (1.2%) $\pi^0 \rightarrow \gamma\gamma$ 98.8%)
conversion $\gamma \rightarrow e^+e^-$

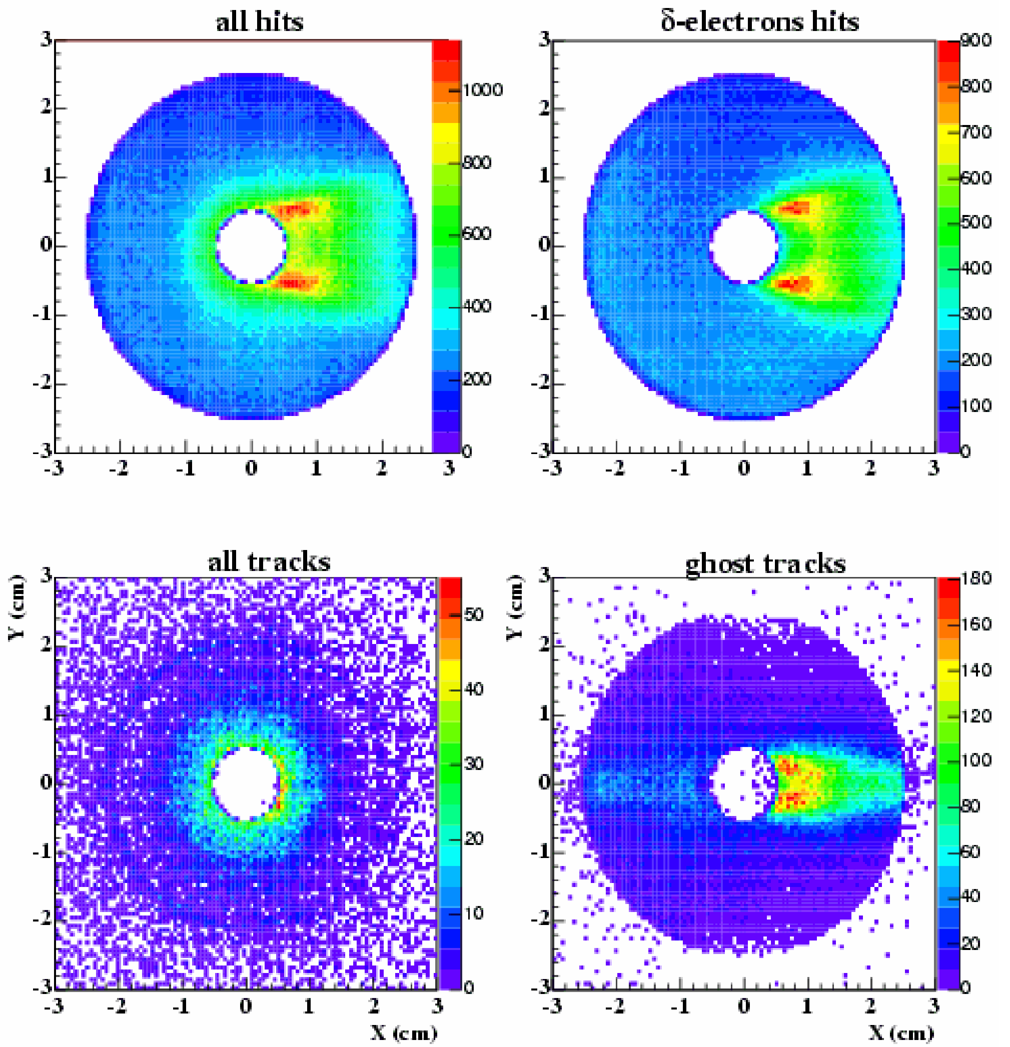


Detector requirements:

- first stations with large acceptance
- tracking efficiency down to p = 0.1 GeV/c to suppress background
- detect conversion pairs: → small pixels

Delta Electrons

δ hits in 1st MAPS station: 1000 min. bias URQMD events, Au+Au 25 AGeV.



<u>Beam ions on target:</u>

⇒ produce delta-rays

⇒ dominate occupancy when integrated over many events.

⇒ high local radiation damage, comparable to bulk damage.

⇒ hits spoil track finding
⇒ limits rate capability

<u>Only way out:</u>
Fast detector readout
to avoid electron hit pile-up.

study by I. Vassiliev, GSI

Data-Push Architecture, Data Flow

- Each detector channel detects **autonomously** all hits
  → FEE design.
- An **absolute time stamp**, precise to a fraction of the sampling period, is associated with each hit.
- **All hits are shipped** to the next layer (usually data concentrators).
- Association of hits with events done later using time correlation.

<u>Typical parameters:</u>

(few % occupancy, 10^7 interaction rate)

- some 100 kHz hit rate per channel
- few MByte/sec per channel
- whole CBM detector: ~ 1 Tbyte/sec